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PROPERTIES OF CHIRPED GRATING LENSES IN OPTICAL
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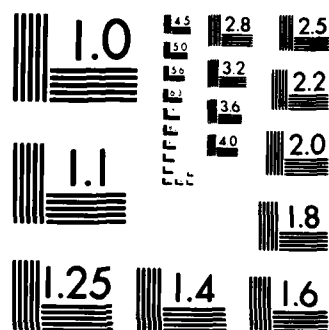
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Properties of Chirped Gratings Lenses in Optical Waveguides

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Introduction

For signal processing in planar waveguides it is necessary to integrate, focus, collimate, image or Fourier-analyze guided wave beams by efficient and low cost lenses and reflectors that have both diffraction-limited performance and low noise.

Currently the most commonly used guided-wave lens is a geodesic lens that requires the precision grinding of the non-spherical surface contour for each lens^[1,2]. Such a fabrication process is quite expensive. Lens effects can also be obtained by diffraction from surface relief patterns made by much less expensive planar micro-fabrication techniques. A linearly chirped grating lens is illustrated in Figure 1. There are two types of diffraction lenses, the Fresnel lens and chirped grating lens. Fresnel lenses have been reported to give diffraction-limited focused spot size, 10° angular field of view and reasonable efficiency at $F > 5$ ^[3-5]. In order to improve the efficiency, chirped grating lenses utilizing volume interaction has been investigated with efficiency reported as high as 90%^[6-9]. The major difference between the Fresnel lens and the chirped grating lens is the length of the grooves. Both the chirped grating lenses and the reflectors can be regarded as a form of one dimensional hologram. The Fresnel lens is a thin phase hologram while the chirped grating (or reflector) is a thick volume phase hologram. However, they differ from the conventional holograms in that a much more sophisticated pattern of the index variation in the longitudinal direction (i.e. in the depth direction of the hologram) can be created by photo lithography and planar microfabrication processes. For example, the material index, the grating groove pattern in both the transverse and the longitudinal direction and the profile of the grooves can all be varied, while in conventional holograms only the index variation in the form of the interference pattern of two optical beams can be created in the

hologram construction process. For example, Figure 2 shows a curved chirped grating lens where the grooves are curved to satisfy more accurately the phase matching condition when the F -number is small or when the grooves need to be long.

In order for a diffraction lens to be useful in guided wave signal processing applications, it must have a high diffraction efficiency η , a diffraction limited focused spot size σ , a reasonably large angular field of view $\Delta\theta$, a desired wavelength selectivity $\Delta\lambda$ and a high signal to noise ratio S/N . In order to realize these performance goals, it is necessary to investigate both theoretical design methods and microfabrication technologies that will allow us to take advantage of index and groove shape control in the depth direction to optimize their design.

Results and Discussion

References 8 to 16 represent research conducted at UCSD supported in part by AFOSR grant 80-0037. Work reported in references 8, 9 and 12, were also supported in part by TRW subcontract on Optical Diffraction Elements under A.F. Prime Contract F33615-82-C-1751. The results reported in these references and some initial results obtained for chirped grating reflectors will be summarized in the following discussions. More specifically, we will discuss:

- (a) A generalized coupled mode analysis that has been used to design chirped grating lenses and reflectors.
- (b) The realization of such a lens in Ti-indiffused LiNbO_3 by depositing rutile grating grooves.
- (c) The difficulties of realizing simultaneously high efficiency and large angular field of view (or high efficiency and low F -number) in the high index T-indiffused LiNbO_3 waveguides.
- (d) The alternative solutions of using the Nb_2O_5 and the ion-exchanged LiNbO_3 transition waveguides.

(e) The fundamental limitations of the lens performance due to diffraction and fabrication tolerance.

Figure 3 illustrates a few examples of chirped grating lenses that can be designed according to the phase matching conditions of the generalized two-dimensional coupled mode analysis^[10] for a given set of desired incident and diffracted beams. Figure 4 shows an example of the calculated efficiency η and the focused spot size of a F/10 linear chirped grating lenses on LiNbO_3 waveguides as a function of the incidence angle when the coupling coefficient K_c can be large. The general conclusion reached in reference 14 is that diffraction limited spot size and high efficiency can be obtained on both low index glass waveguides and high index LiNbO_3 waveguides and when $K_c d = \pi/2$ and when the F-number is relatively large (eg. $F = 20$). However, the angular field of view of a linearly chirped grating lens may be very small if long grating groove lengths are needed for small K_c to obtain high efficiency. Large angular field of view at small K_c can only be obtained at the expense of lower efficiency. Similarly the efficiency will drop for small F-number lenses where K_c is small. Thus, in order to get a combination of high efficiency and reasonably large angular field of view (or large η and low F), one must develop materials technology that will yield large K_c .

Materials technology (in particular the deposition of CeO_2) to obtain a large coupling coefficient in glass waveguide lenses has been developed at UCSD and high efficiency with $\Delta\theta = 0.1$ radians has been obtained experimentally^[13]. The extension of $\Delta\theta$ to larger values using shorter groove length is limited primarily by the diffraction into higher orders of diffraction when the Q-factor ($Q = 2\pi\lambda ed/\Lambda^2$) is less than 10^[15,17]. The situation is quite different in LiNbO_3 waveguides^[12].

Experimentally, we have investigated different materials and processes for

the fabrication of grating grooves on LiNbO_3 waveguides that will yield reasonably large K_c values^[8,9,12]. Figure 5 shows the calculated K_c that can be obtained by etching LiNbO_3 and by depositing TiO_2 for two different mode depths^[12]. Notice that high resolution thin grating patterns and moderately large K_c can more easily be obtained by depositing thin TiO_2 layers on waveguides. For a given mode depth, a limit on the K_c value is the TiO_2 thickness (or the etched depth) within which one and only one single TE mode will propagate. A small mode depth is also necessary in order to get large K_c . Hard transparent and durable films of TiO_2 with a 2.6 refractive index have been obtained in our laboratory by electron beam evaporation of Ti followed by oxidation in an oxygen atmosphere at 450°C. However, the practical mode depth of the Ti-indiffused waveguide for single mode propagation is limited by the minimum diffusion time required for a given thickness of deposited Ti below which there will be residue of undiffused Ti compound left on the waveguide surface. A shallower mode depth (i.e. a larger K_c) can be obtained when water vapor is added in the diffusion process^[18]. Figure 6 shows that the largest Δn_{eff} (i.e. the change of n_{eff} in LiNbO_3 single mode waveguide with or without TiO_2 overlay) that we have been able to obtain experimentally is .014. However, mode conversion to substrate modes begins at 500Å of TiO_2 caused by the step discontinuity of the deposited layer. Thus the maximum usable Δn_{eff} in LiNbO_3 Ti-indiffused waveguides is only 0.005.

In short, we have found that the limitations in K_c were caused primarily by the mode depth of the Ti-indiffused waveguide. The small K_c obtained in the Ti-indiffused waveguide severely limits the angular field of view of any efficient chirped grating lens. Our data have also shown that it is difficult to reproduce the Δn_{eff} in Ti-indiffused waveguides. On the other hand, we have also found substantial coupling of the guided wave power into the substrate modes

under certain circumstances. It is caused primarily by the closeness of the n_{eff} of the guided wave mode to the substrate index n_s . Therefore, we may attribute the difficulties of both the very small angular field of view and the substrate mode conversion to the basic properties of Ti-indiffused waveguides, namely large mode depth and $(n_{\text{eff}} - n_s)/n_s \ll 1$.

As shown in Figure 7, all our gratings and grating lenses are fabricated by replication of the Cr mask pattern onto a LiNbO_3 waveguide spin coated with photoresist by the conformable contact printing method. The Cr masks have been made by electron beam lithography at the NSF National Research and Resource Facility for Submicron Structures at Cornell University, Ithaca, New York. A Ti layer is then evaporated by the electron beam evaporation method onto the sample that already has the desired resist pattern, and a Ti grating or grating lens pattern is obtained using the lift-off technique. Patterns of up to one μm line width seem to be able to be reproduced by this process. The lift-off method was used instead of the more commonly used wet etching method because it gives a higher resolution. TiO_2 patterns are obtained from Ti patterns by oxidation. Alternatively C_2F_6 has been used in our laboratory for reactive ion beam etching of grating grooves^[19,20]. The etching rate is about 600Å/min at a beam current of $.3\text{mA}/\text{cm}^2$.

Clearly we need an alternate waveguide in LiNbO_3 that has small mode depth, large n_{eff} , low attenuation and small inplane-scattering noise. If Ti-indiffused waveguides must be used for other elements such as acousto optical diffraction in the r.f. spectrum analyzer, then the alternate waveguide may be used as a transition waveguide interconnecting two sections of a Ti-indiffused waveguide. After examining the various possibilities we have come to two solutions. The first solution would be to fabricate a Nb_2O_5 transition waveguide as shown in Figure 8. The energy in the LiNbO_3 indiffused waveguide is lifted into the input

tapered section of the Nb_2O_5 waveguide, diffracted by the grating lens and then converted back into the LiNbO_3 waveguide mode at the output tapered section. The best total measured insertion loss of the transition including the taper is 0.8 dB. Because of the large index of Nb_2O_5 guiding layer, small mode depth and large K_c coefficient was obtained. The measured throughput efficiency and angular field of view of the lens are $85\% \pm 5\%$ and 4 degrees for an $F = 12$ lens with $\Lambda_{\min} = 1.73 \mu\text{m}$, $\Lambda_{\max} = 3.45 \mu\text{m}$ and $40 \mu\text{m}$ groove length. The second potential solution is to make a transition waveguide interconnecting two sections of a Ti-indiffused waveguide by proton exchange^[9]. An ion exchanged chirped grating lens can be made by employing a second ion exchange process using an Al mask. In this case, there is no observable substrate mode conversion effects, since the n_{eff} of the guided mode is quite high, approximately 2.265. The measured throughput efficiency and the angular field of view are 75% and 4 degrees for the same lens pattern as that on the Nb_2O_5 transition waveguide when the groove is $80 \mu\text{m}$. Alternatively the ion exchange process may be used to make a chirped grating pattern of high index regions inside a Ti-indiffused waveguide through an Al mask.

The performance of all the waveguide lenses is fundamentally limited by the diffraction properties of chirped gratings in two different ways. (a) Limitations in the coupling coefficient means that tens of micrometers of groove length is required to obtain high efficiency. For a linear chirped grating lens this means that phase distortions (i.e phase mismatch) will occur at long groove length or small F numbers. Figures 9 and 10 show the calculated and measured maximum diffraction efficiency and angular field of view of a linearly chirped grating lens as a function of groove length (or K_c , with $K_c d = \pi/2$)^[14]. The drop in efficiency is caused primarily by phase distortion, especially for small F -number lenses. Alternatively as shown in Figure 3, curved chirped grating

lenses may be used to provide perfect phase matching for long groove length and small F-numbers. However, the angular field of view of chirped grating lenses is extremely small. Ultimately, the smallest F-number of a grating lens will be limited by the minimum grating periodicity Λ_{\min} that can be etched or deposited. This limitation is expressed as

$$F_{\min} = \Lambda_{\min} n_{\text{eff}} / \lambda_0$$

where λ_0 is the free space wavelength. (b) Limitation in grating periodicity implies also that Raman-Nath diffraction may occur when the groove length is too short. A rigorous coupled mode analysis has been formulated by Moharam and Gaylord^[15,17] that gave $1/\rho^2$ ($\rho = \lambda_0^2 / \Lambda^2 n_{\text{eff}} \Delta n_{\text{eff}}$) as the upper bound of the fraction of power diffracted into higher orders for constant periodicity gratings. Their calculated results have been confirmed experimentally by us^[15]. Thus the ρ factor imposes another limitation on the diffraction efficiency of chirped grating lenses.

Summary

In conclusion, in integrated optical circuits one must combine materials technology with theoretical analysis in order to realize the desired performance goals of chirped grating lenses. Efficient chirped grating lenses can be realized effectively in both the glass and the LiNbO₃ waveguides. An angular field of view of several degrees may be obtainable for lenses in LiNbO₃.

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Several of my students and colleagues, S. Forouhar, J. M. Delavaux, C. Warren, Z. Q. Lin and S. T. Zhou have made major contributions in this work. Dr. S. K. Yao of TRW collaborated with us in the LiNbO_3 waveguide lens work. The mask patterns have been fabricated by electron beam lithography in the NSF National Research and Resource Facilities at Cornell University. Hence, this work is supported in part by AFOSR, TRW and NSF.

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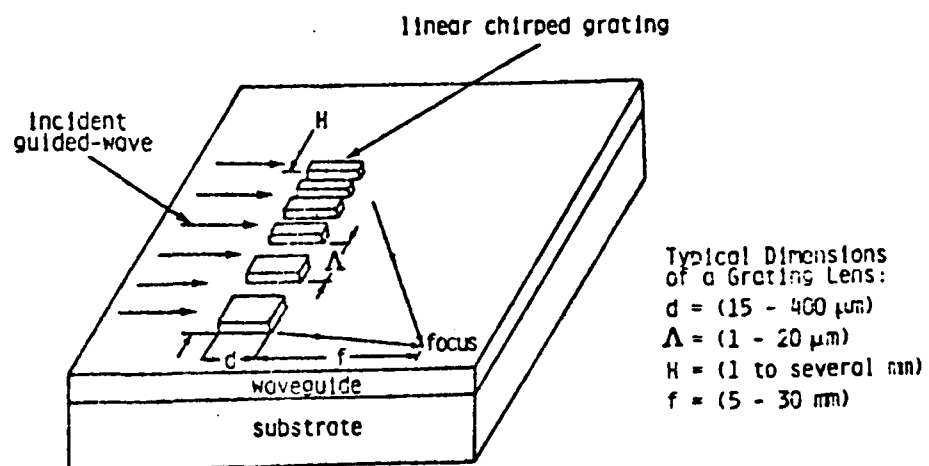


Fig. 1 Illustrations of a Linearly Chirped Grating Lens

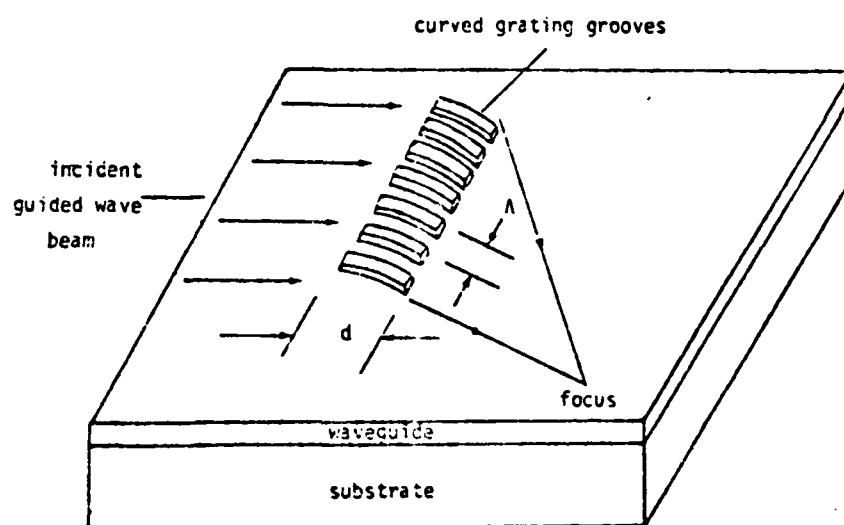


Fig.2 Illustration of a Curved Chirped Grating Lens

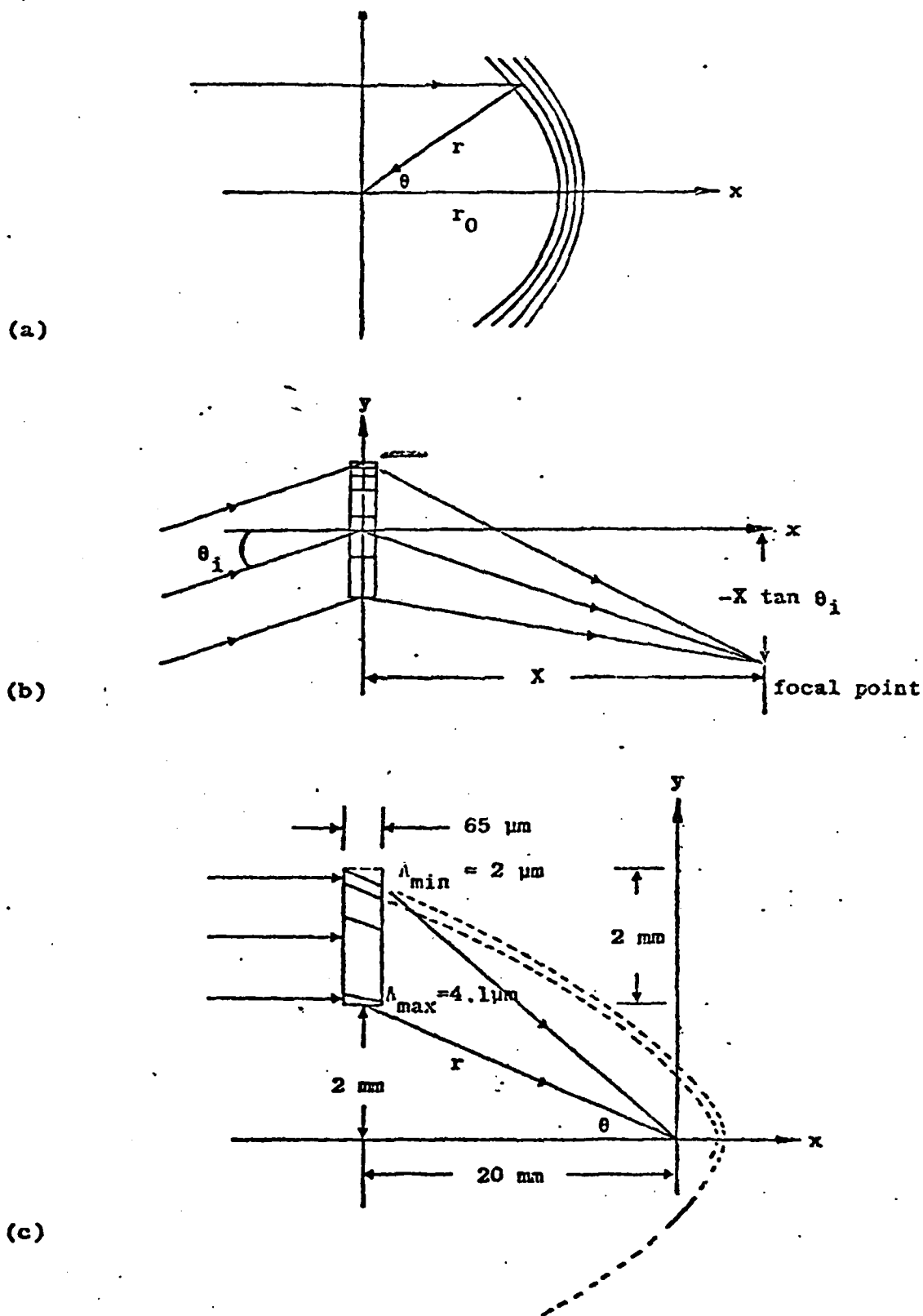


Fig.3 Examples of Diffraction of Guided-Wave Beams by Chirped or Curved Gratings (a) a chirped grating reflector, (b) a linearly chirped grating lens in which the curved patterns are approximated by linear grating grooves, and (c) a curved chirped grating pattern to satisfy exactly the phase matching condition.

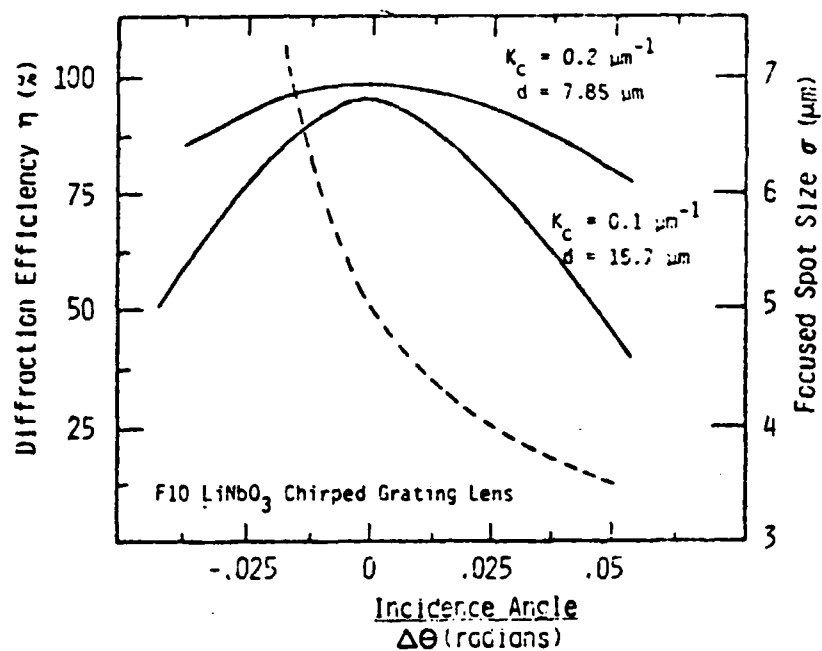
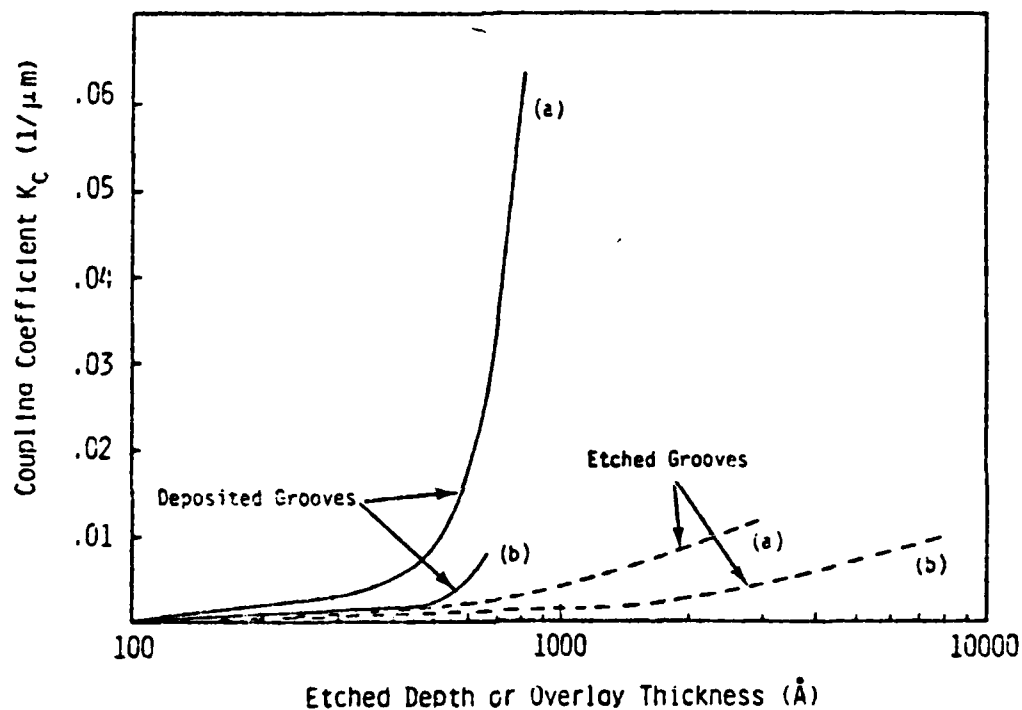
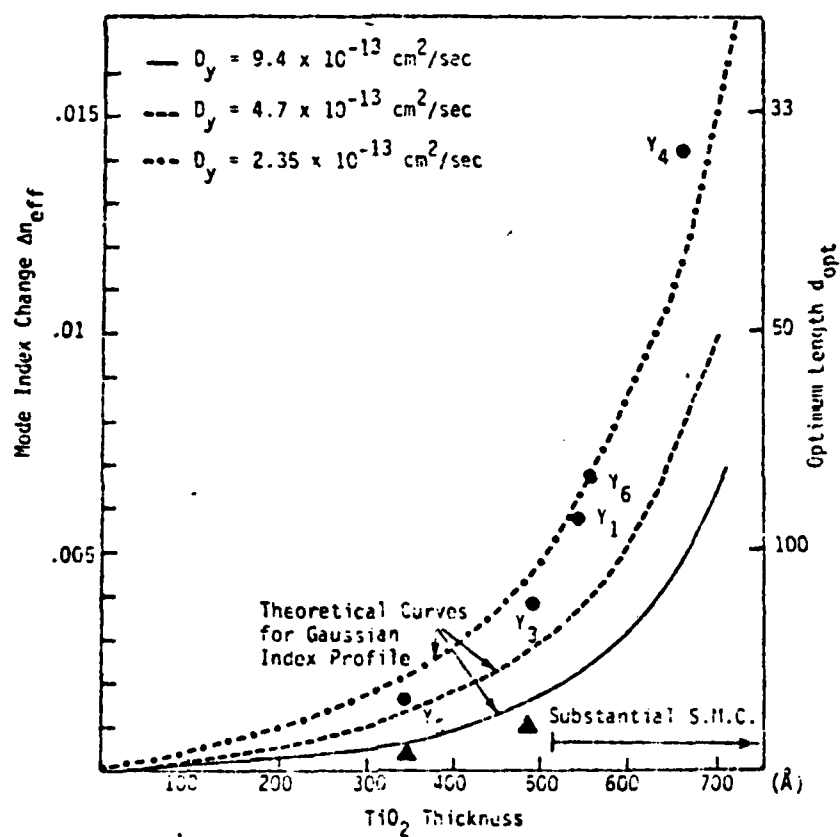


Fig. 4 Calculated Diffraction Efficiency and Spot Size of a LiNbO₃ Linearly Chirped Grating Lens



- (a) The effective mode depth of the waveguide is $1 \mu\text{m}$.
 (b) The effective mode depth of the waveguide is $2 \mu\text{m}$.

Fig. 5 The Coupling Coefficient of the Etched or the Deposited Chirped Gratings on LiNbO_3 Waveguides



● Experimental results when water is at 95°C during diffusion.

▲ Experimental results when water is at room temperature (25°C).

Fig. 6 The Mode Index Change of the Deposited Gratings on Ti-indiffused LiNbO_3 Waveguides.

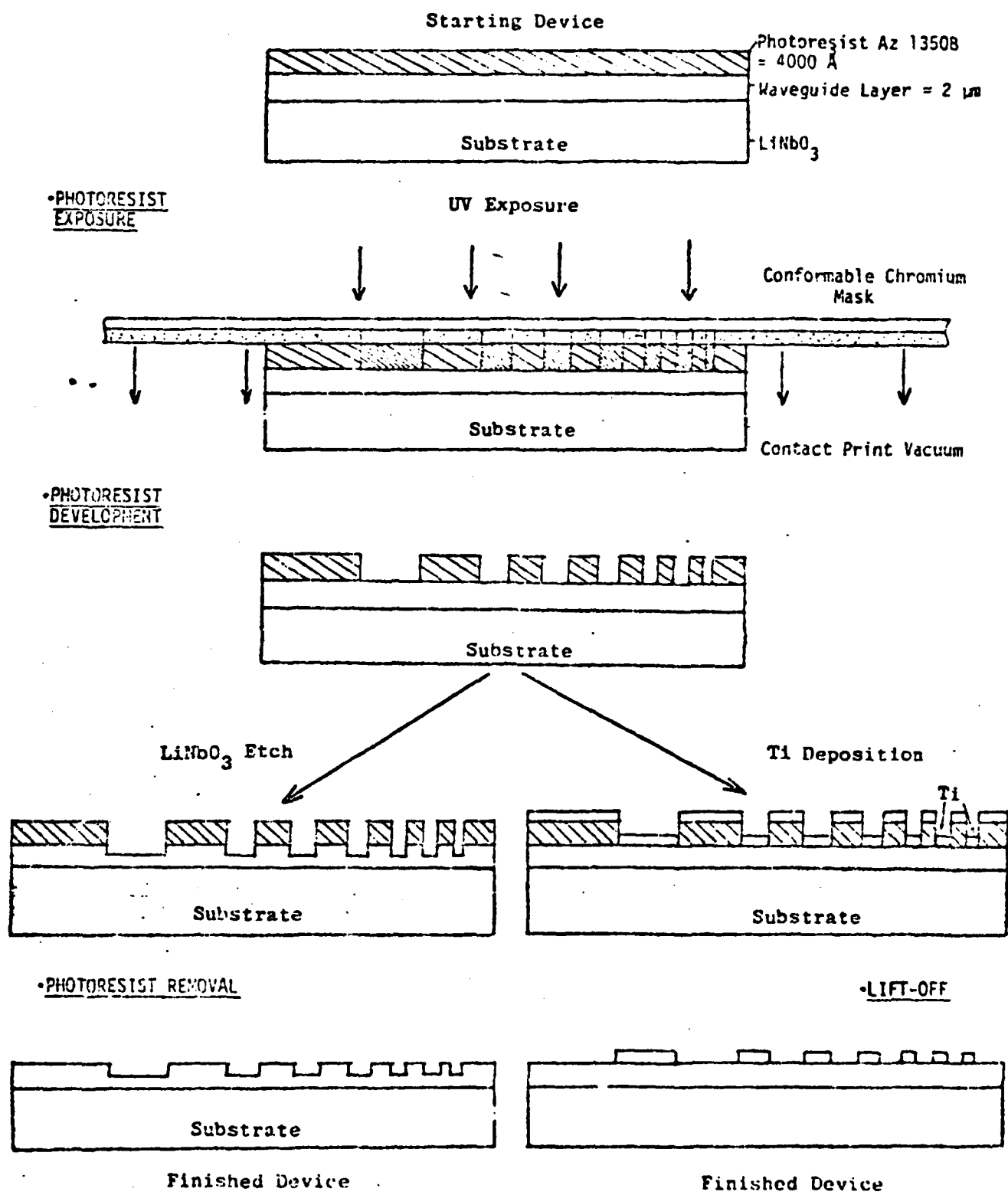
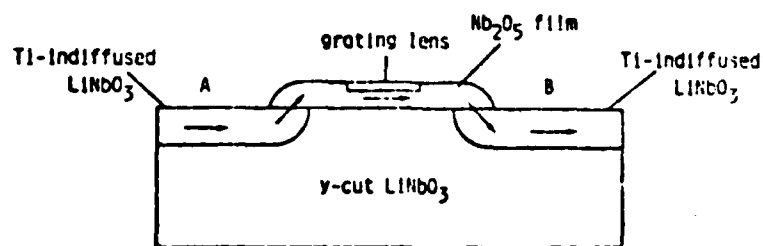
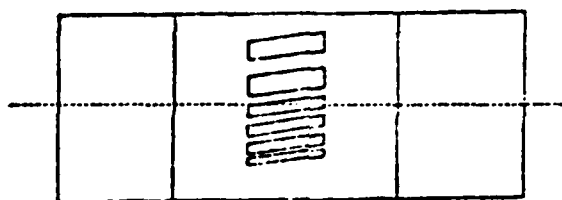


Fig. 7 Fabrication Processes of the Chirped Gratings



Side View of Mode-Lift-Off Structure



Top View of Mode-Lift-Off Structure

Fig. 8 Illustration of the Nb₂O₅ Transition Waveguide

Linear Chirped Grating Lenses

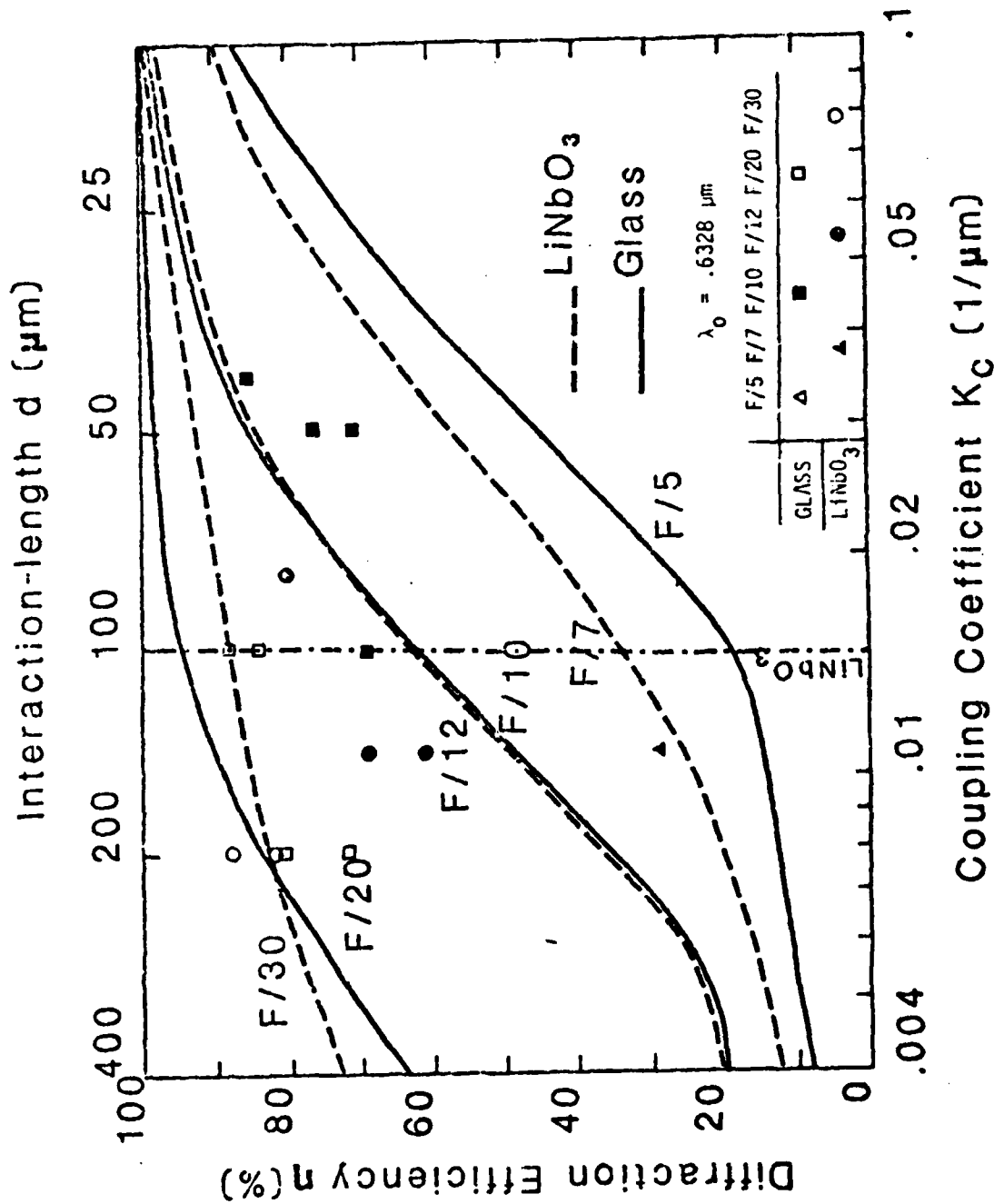


Fig. 9 Diffraction Efficiency Limitations of Linearly Chirped Grating Lenses

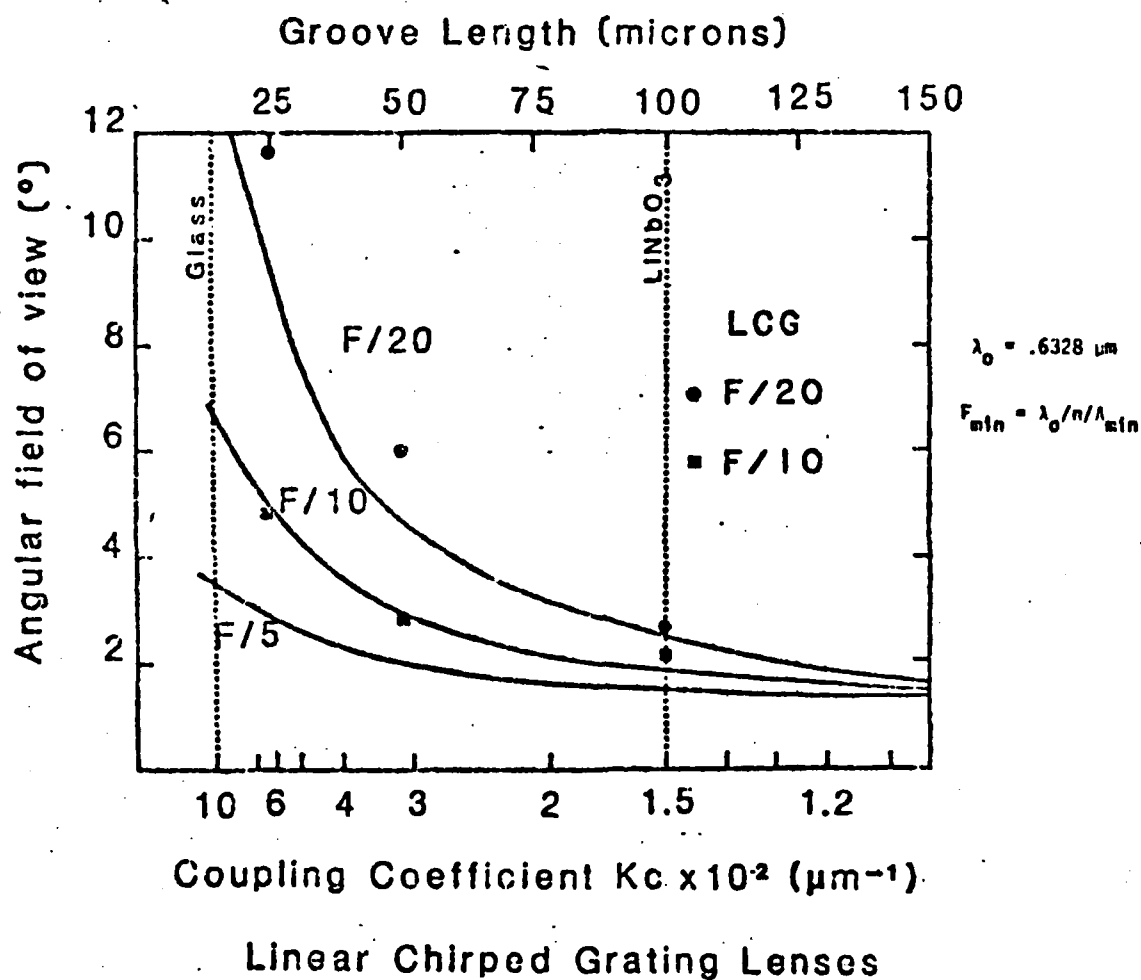


Fig. 10 Angular Field of View Limitation of Linearly Chirped Grating Lenses

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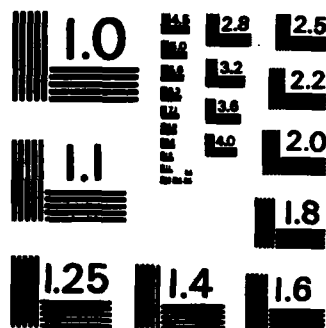
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